Foundation Problems and Solutions at the Bridge River, Powerhouse No. 1

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SYNOPSIS The Bridge River Powerhouse No. 1 was constructed between 1946 and 1950 on the north shore of Seton Lake near Lillooet, British Columbia, Canada. The Powerhouse contains four Pelton wheel (impulse) turbines generating a total of 200 MW of electrical power. When the powerhouse was completed and the first units placed in operation severe and extensive ground cracking occurred behind and beyond the powerhouse. The ground movement shifted the powerhouse slightly toward the lake, and cracked the concrete penstock tunnels. As a result of this the foundation under the powerhouse was thoroughly investigated and instrumentation installed to record and assess further movement. Drs. K Terzaghi, V. Dolmage, A. Casagrande and later Dr. R.M. Hardy provided expert advise on assessing the problem and devising remedial measures. This paper reviews the causes of cracking, 33 years of powerhouse instrumentation data and remedial measures carried out to stabilize the powerhouse.

INTRODUCTION

Powerhouse No. 1 is located at the foot of Mission Ridge, El. 1540 m, in the coastal mountain range in British Columbia, Canada. The powerhouse is located on the north shore of Seton Lake. Water for the turbines is diverted from Bridge River (about 420 metres above Seton Lake) through Mission ridge to the powerhouse. About 4 Km of concrete lined tunnel and steel penstock transport water to Powerhouse No. 1 as shown on Fig. 1.

For the proposed development, it was decided to found the powerhouse on dense glacial till existing along the north shore of Seton Lake. Rock at this location was not encountered in the exploratory drill holes. The development planned for an ultimate 10-units in the one powerhouse by extending the proposed 3-unit powerhouse to the west for future development. After ground cracking and powerhouse movement the proposed extension was abandoned.

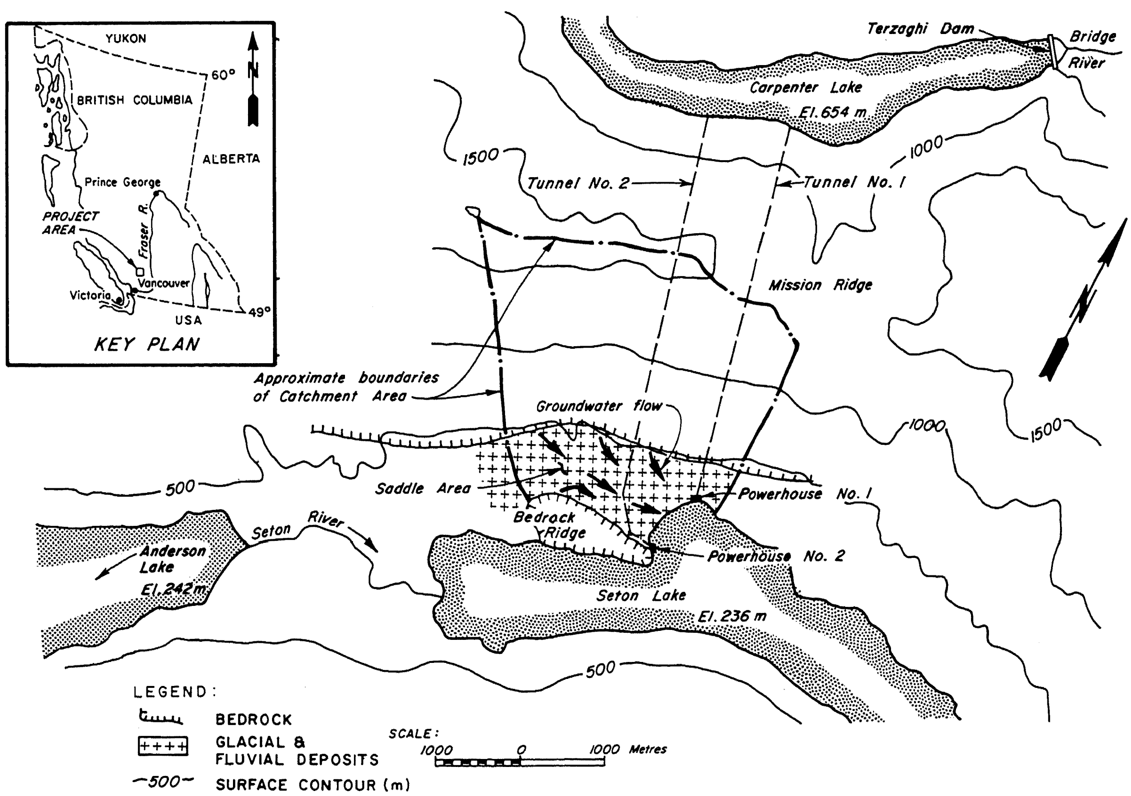

Fig. 1. Location Plan

GEOLOGICAL AND HYDROLOGICAL CONDITIONS

The Seton Lake area has undergone several glacial advances and retreats during the late Pleistocene or recent past. Sediments encountered consist of an interfingered series of glacial tills, interglacial (fluvial) silts and clays, sands, gravels and talus deposits derived from weathering of exposed bedrock outcrops.

The powerhouse is situated on the north shore of Seton Lake at the foot of a steep mountain slope, see Fig. 2. The upper portion of the slope consists of exposed bedrock, and the lower portion consists of overburden material extending into Seton Lake at a relatively flat slope, as shown on Fig. 3.

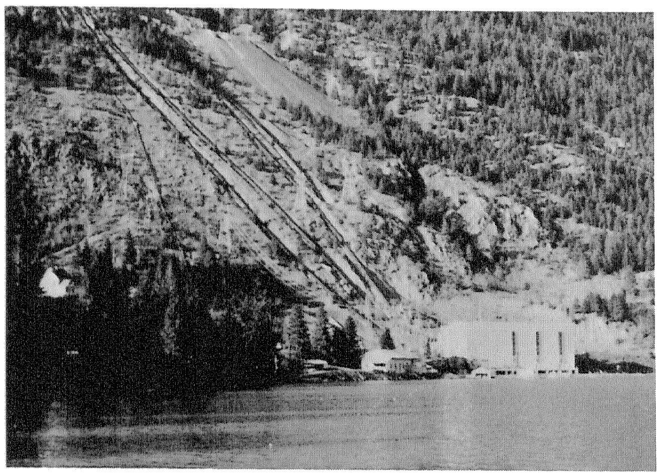

Fig. 2. Powerhouse No. 1 and Penstocks 1 to 4, April 1983.

The bedrock in the area consists of a fine grained igneous andesite, known as greenstone, and some low grade metamorphic quartzite. The upper ten (10) metres is generally highly fractured and weathered, and permits flow of groundwater.

The overburden material near Powerhouse No. 1 consists of a dense glacial till to a depth of about 20 m. Below the glacial till is a zone of clayey silt also about 20 m thick underlain by artesian silt, sand and gravel of unknown thickness. Drillhole No. 76-3, installed approximately midway between Powerhouse Nos. 1 and 2, extended to a depth of approximately 110 metres without encountering bedrock. The impervious clayey silt stratum extends out beneath Seton Lake confining flow from the uphill area within the underlying aquifer. A geological section through Powerhouse No. 1 is shown on Fig. 4.

To the southwest of Powerhouse No. 1 there is a rock ridge on which Powerhouse No. 2 is located. The bedrock ridge serves to confine and restrict the flow of groundwater. Groundwater from the catchment area is funnelled toward Seton Lake between the bedrock ridge to the south and the bedrock, at the foot of Mission Ridge to the north. Between Powerhouse No. 1 and the rock ridge an overburden saddle rises several hundred metres above Seton Lake and extends about 2 km back from Seton Lake.

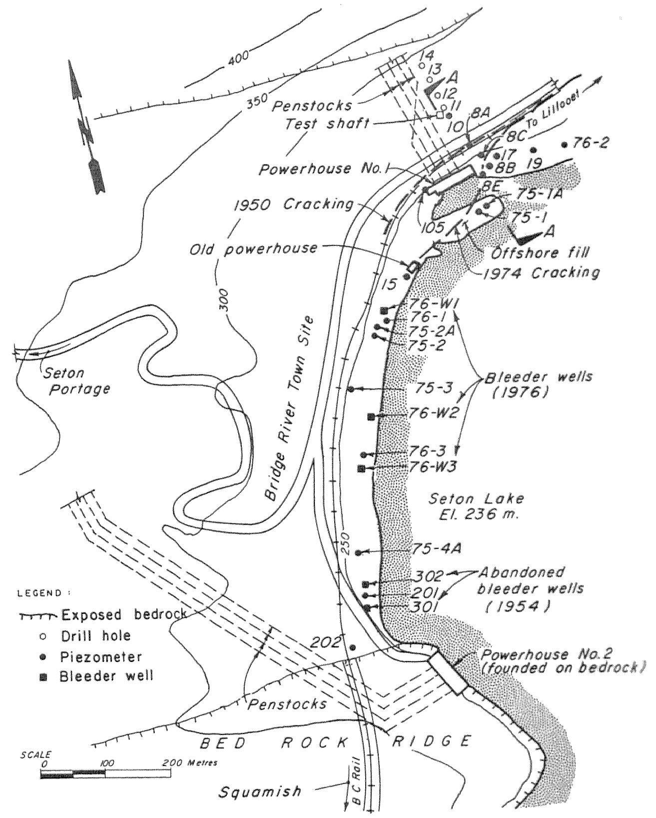

Fig. 3. Site Plan - 1983

The catchment area extends over about 14 km^2 and feeds the aquifer between the powerhouses. Run-off water from the mountainsides flows through the steep fractured bedrock to the basal sands and gravels towards Seton Lake, where it is restricted by the overlying clayey silt strata, see Fig. 4. The uphill feed of ground water into the aquifer and the restricted outlet at lake level causes high artesian pressures during each spring's snowmelt and runoff. High artesian pressures develop in the aquifer below the powerhouse and below the entire shoreline.

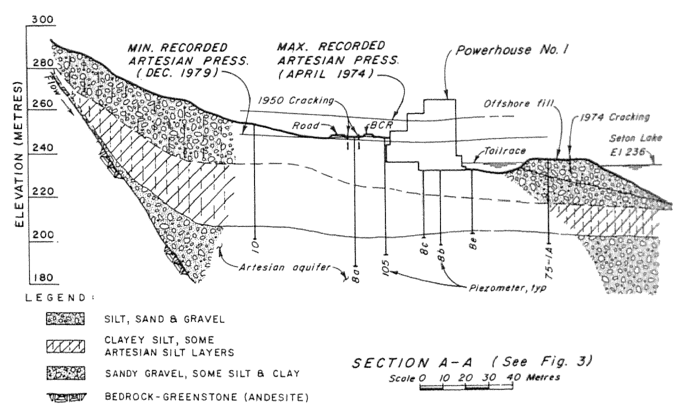

Fig. 4. Geological Section through Powerhouse No. 1

INVESTIGATIONS AND CONSTRUCTION DIFFICULTIES UP TO JANUARY 1950

Exploratory work at the powerhouse site commenced in June 1928 when two holes were drilled. The stratigraphy encountered indicated silt, sand and gravel to a depth of about 12 m. Beneath which a dense clay with sand and gravel layers extended to a depth of about 30 m. Some artesian water flow was encountered from the bottom of the deepest hole.

The investigation, design and site supervision was undertaken by Shawinigan Engineering Company Ltd. Seven exploratory holes were drilled extending to a maximum depth of about 24 m. These holes did not extend through the clayey silt to intersect the artesian pressure in the sand/gravel aquifer.

The shortest route from Carpenter Lake to Seton Lake was selected for the tunnel and penstock location with the powerhouse sited as close as possible to the proposed diversion facilities (Fig. 1). In 1946 work on the powerhouse was commissioned by the B.C. Electric Railway Company Ltd. (now B.C. Hydro).

The powerhouse foundation work commenced in August 1947 and the powerhouse was completed in September 1949. From 1948 to 1949 settlement measurements indicated that the powerhouse had tilted slightly to the north (i.e. uphill).

The tilt was caused by differential settlement of the underlying clayey silt layer because this stratum was thicker beneath the north end of the powerhouse than beneath the south end. The tilting at that time was not a serious concern.

Inspection of the powerhouse revealed no significant cracks in the concrete. However the uneven settlement of the powerhouse caused problems with the No. 1 Generator thrust bearing. Despite the equipment alignment problem there was no indication of a potential long-term serious problem.

GROUND CRACKING IN 1950 AND SUBSEQUENT INVESTIGATIONS

In the four days from 21 to 25 April 1950, Seton Lake had been lowered 0.5 m from El. 235.4 to El. 234.9 as a result of channel deepening in Seton Creek at the outlet of the lake.

On 28 April 1950, the following events occurred:

I. Extensive cracking occurred behind and beyond the powerhouse.

II. The concrete penstock tunnels under the road and railway, through which the penstocks pass into the powerhouse developed cracks up to 6 mm wide. This indicated that the powerhouse had shifted towards the lake.

III. A small penstock to the Old Powerhouse had lengthened 2 mm at an expansion joint.

IV. The 100 mm water main from the temporary plant to the townsite fractured.

V. The B.C. rail track, about 250 m east of Powerhouse No. 1 had settled up to 200 mm and moved out of alignment.

These events caused considerable concern about the security of the powerhouse. Dr. V. Dolmage (B.C. geologist) was consulted and he advised the B.C. Electric Company to seek the assistance of Dr. Terzaghi on this serious matter. A detailed survey of the ground cracks revealed that they ranged from 0.3 to 7.6 mm wide in an arc around the powerhouse and ran several hundred metres along the railway tracks as shown on Fig. 5.

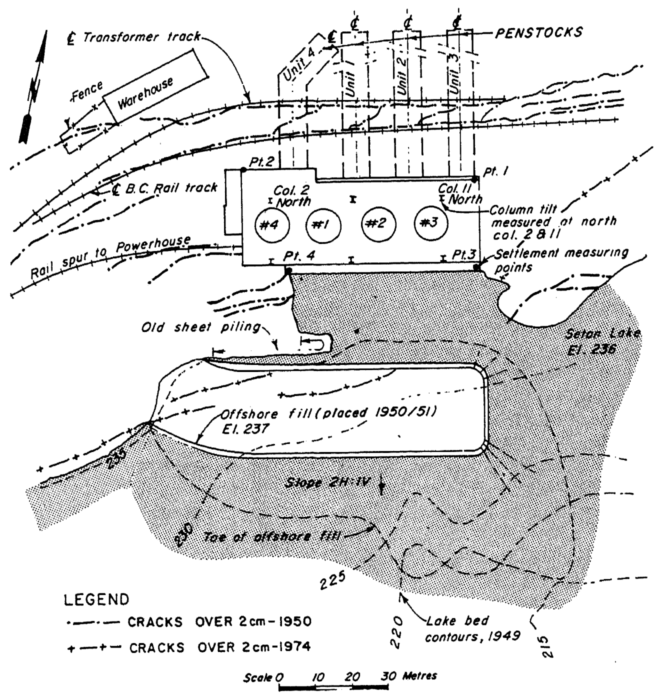

Fig. 5. Ground Cracking in 1950 and 1974 and Instrumentation - 1951

During the initial assessment of the ground movements it was believed that lowering of the lake level was the cause. However Dr. Dolmage was of the opinion that water under pressure from the tunnels could be causing high uplift under the powerhouse. Dr. Dolmage also indicated that surface flows could be feeding the aquifer high up the hillside. He therefore recommended that surface water be diverted directly to the lake.

Dr. A. Casagrande was retained by Shawinigan Engineering Ltd. and briefly studied the movement of Powerhouse No. 1 He concluded that a possible cause of the cracking was consolidation of the clay layer due to lowering of the lake level.

In 1950 the B.C. Electric Company retained Dr. Terzaghi to assess the powerhouse problem. He recommended an extensive monitoring program which was then commenced to measure powerhouse settlement and tilt, penstock elongation, crack widths, transformer and tower footing settlements.

Penstock elongation measurements were also undertaken to assess horizontal movement of the powerhouse.

Dr. Terzaghi on assessing the drill hole data from the pre-construction investigation and the general terrain of the area agreed with Dr. Dolmage's assessment that the powerhouse was located on an ancient landslide. Dr. Terzaghi requested that a detailed investigation be carried out including deeper drill holes, testing and excavation of a vertical shaft.

The deep drill holes encountered the aquifer below the clay silt zone and confirmed the existence of high artesian pressure. The vertical shaft extended to a depth of 19 m but did not extend to the artesian layer. Further detailed investigations continued from 1950 to 1951.

GROUND CRACKING IN 1951 AND PLACEMENT OF OFFSHORE FILL

On 9 April 1951 and during the next few days, new cracks appeared to the west of the powerhouse and several hundred metres to the east of it. This new cracking coincided with a sharp rise in the artesian water pressure and occurred during the spring snowmelt - high runoff period. About 200 m east of the powerhouse the railway tracks settled and required raising and reballasting. Also a fissure developed in the ground, adjacent to drillhole 15 (see Fig. 3), discharging silty water. This fissure was sealed off by installing 250 mm casing over the existing casing at drillhole 15, after the artesian pressure had dropped.

Dr. Terzaghi advised that the presence of high artesian pressure and its seasonal fluctuation was proven by the field investigations and monitoring program.

In July 1951, Drs. Terzaghi, Dolmage and Casagrande met with B.C. Electric and Shawinigan engineers at the site and reviewed the results of the investigations. They reviewed the results of the 1950 and 1951 drilling information. The causes of the problem and possible solutions were discussed. It was agreed that the principal cause of cracking was due to a high artesian pressure and that lowering of the lake level was only a minor contributor to the decrease in resistance to sliding.

Following these discussions Dr. Terzaghi requested that some bleeder well tests be carried out to see if the artesian pressure could be kept at a low level. However near the powerhouse, where the test was performed, fine silt existed below the clayey silt stratum and the artesian water removed contained large quantities of silt. To avoid the possibility of severe settlement due to loss of silt Dr. Terzaghi stopped the test and abandoned this method of reducing the artesian pressures.

As an alternative solution Dr. Terzaghi recommended that an offshore fill be placed in front of the powerhouse and that material be excavated from the hillside behind the powerhouse, 68,000 m^3 of fill was placed. Fig. 5 illustrates the location of the offshore fill. Fig. 4 illustrates a typical section through the fill and Powerhouse No. 1.

In order to record and assess powerhouse movement instrumentation procedures were established, in October 1951,by Dr. Terzaghi and have essentially been followed to date. These included artesian pressure gauge readings, settlement observations, tilt readings on columns, elongation of penstock tunnels and crack width measurements. Most of the instruments are read monthly, the artesian pressure gauges are read more frequently in times of high artesian pressure. Details of some of the instrumentation are shown on Fig. 6. Terzaghi's penstock elongation measuring device is shown on Fig. 7.

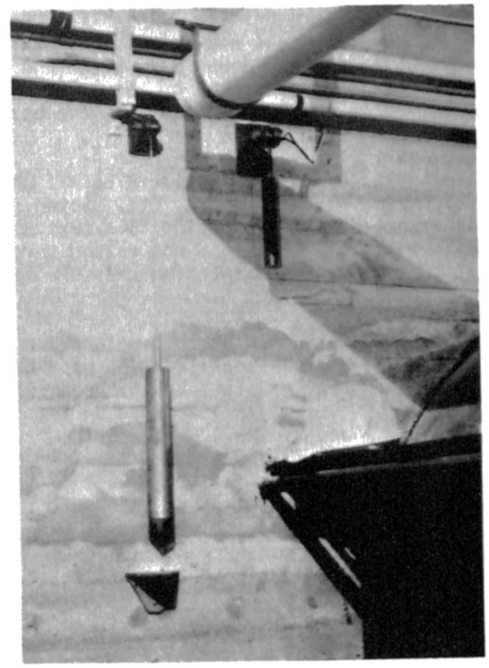

Fig. 6. Instrumentation Details - 1951

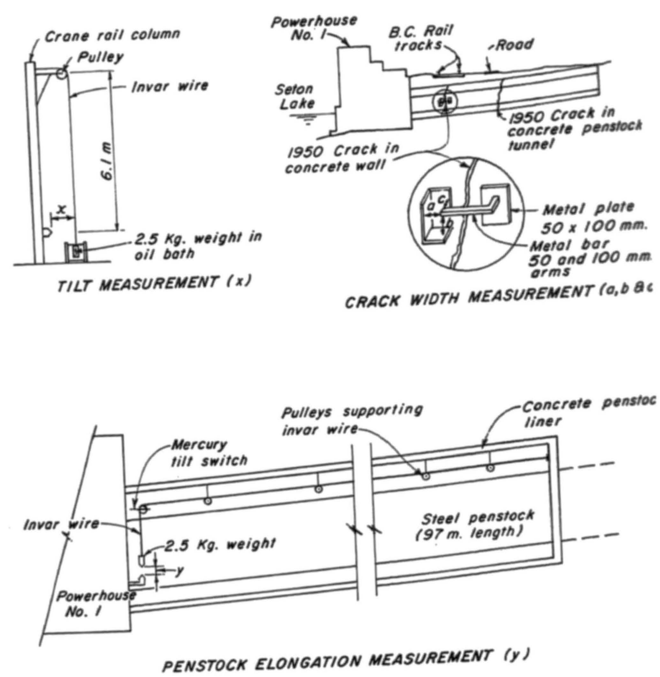

Fig. 7. Terzaghi's Penstock Elongation Measurement Device, April 1983

POWERHOUSE PERFORMANCE 1951 TO 1973

In 1953 very high artesian pressures were recorded near the bedrock ridge south of Powerhouse No. 1. Bleeder wells Nos. 301 and 302 were installed along the shoreline in this area in 1954, unfortunately they did not penetrate a highly permeable stratum and eventually silted up.

In June 1958 the penstock tunnel for Bridge River Powerhouse No. 2 was holed through resulting in a flow of about 20 l/sec. This flow disappeared into the talus material part way down the hillside and fed water into the underlying aquifer causing a steep rise in the artesian pressure under the powerhouse (see Fig. 8) that was out of sequence with the annual runoff peak artesian pressures. The tunnel flow was piped away by 8 July 1958 and the artesian pressures subsided near both Powerhouse Nos. 1 and 2 without causing any ground cracking or subsidence.

In 1959 and earlier it had been observed that two nearby creeks, emerged above ground in times of high artesian pressure and disappeared below ground when the artesian pressures were low. In 1961 it was recommended that the creeks be diverted above the talus material and be carried in a pipeline to Seton Lake. These measures were undertaken in 1962 and serve to reduce inflow into the artesian aquifer in the vicinity of Powerhouse Nos. 1 and 2.

INSTRUMENTATION RESULTS 1953 TO 1983

Instrumentation data indicates that the powerhouse acts as a rigid unit and tilts slightly between summer and winter due to severe changes in temperature. Also, the instrumentation shows that the high artesian pressures in early spring correspond approximately with the cyclical movement of the powerhouse. Piezometer installation commenced in 1950, sufficient were functioning in 1953 to permit the average artesian pressure to be determined. Fig. 8 illustrates the variation in artesian pressure for selected years between 1953 and 1983.

Instrumentation devices were installed which have alarms that would be activated if extensive downhill movement or tilt of the powerhouse was to occur. The penstock elongation indicates southerly (horizontal) movement of the powerhouse towards the lake and column tilt indicates tilt of the top of the powerhouse to the north, typical data from these devices are shown on Fig. 9.

The penstock elongation measurements indicated a cyclical trend of the powerhouse moving southerly in the winter and spring and northerly in the summer and fall. There has been no long term trend of southerly (horizontal) movement of the powerhouse towards the lake but only seasonal fluctuation.

Similarly the powerhouse tilts to the north on a seasonal basis only and shows no long term trend of increasing tilt.

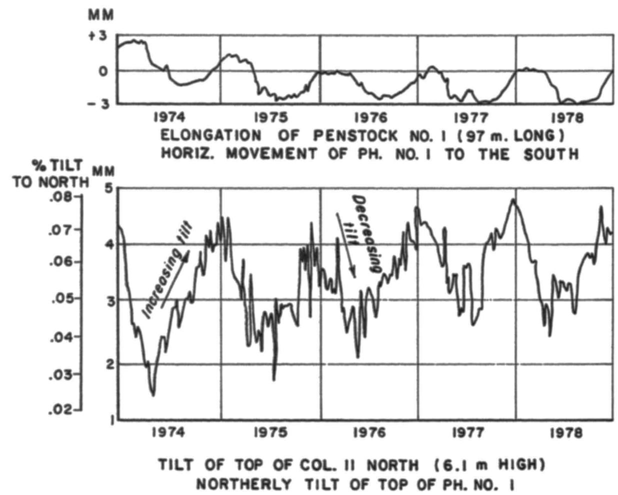

Fig. 9. Typical Instrumentation Results (1974 to 1978)

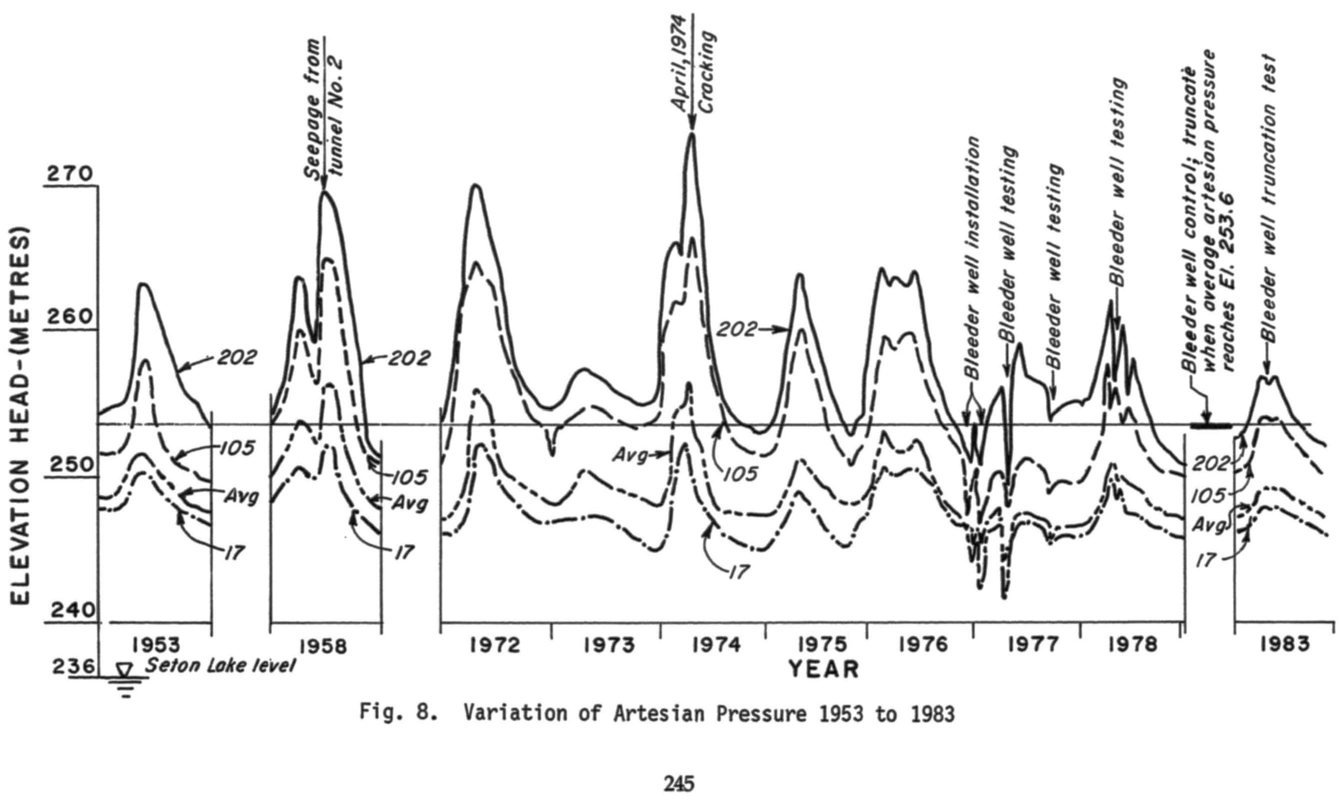

Fig. 8. Variation of Artesian Pressure 1953 to 1983

GROUND CRACKING IN 1974 AND SUBSEQUENT INVESTIGATIONS

In April 1974 ground cracking up to 100 mm wide occurred across the offshore fill in front of the powerhouse and along part of the railway embankment to the east of the powerhouse, as shown on Figs. 5 and 10.

Fig. 10. Cracking in Offshore Fill, April 1974

It was decided to investigate whether a bleeder well system could be developed that would truncate the peak of the artesian pressures to a safe level without causing piping of the silt material. Dr. R.M. Hardy was retained to advise B.C. Hydro on this program.

Dr. Hardy saw no evidence of significant subsidence of soil on the lake side of the crack nor of significant lateral displacement and concluded that the cracks were due to lifting of the fill by the artesian pressures. The occurrence of these cracks did not represent a general deterioration of the subsoil stability conditions beneath the powerhouse. They were described as a re-appearance of the same type of cracks that were observed in 1950 and 1951.

Dr. Hardy recommended that a drilling program be undertaken to see if a pervious sandy-gravel zone could be located where a bleeder well system could be established.

In 1975, holes were drilled along the Seton Lake shoreline between Powerhouses Nos. 1 and 2. These holes, encountered stratigraphy similar to that of the previous drilling, except that a very coarse zone was found at depth in the aquifer, between Powerhouse Nos. 1 and 2. A typical drill log is shown on Fig. 11.

Although the geotechnical and hydrological characteristics of the overburden deposit containing the aquifer were not fully determined, it was considered that installation of bleeder wells could be effective in reducing excessive artesian pressures provided the well screens could be located in a coarse sand and gravel layer within which a highly pervious natural filter could be developed.

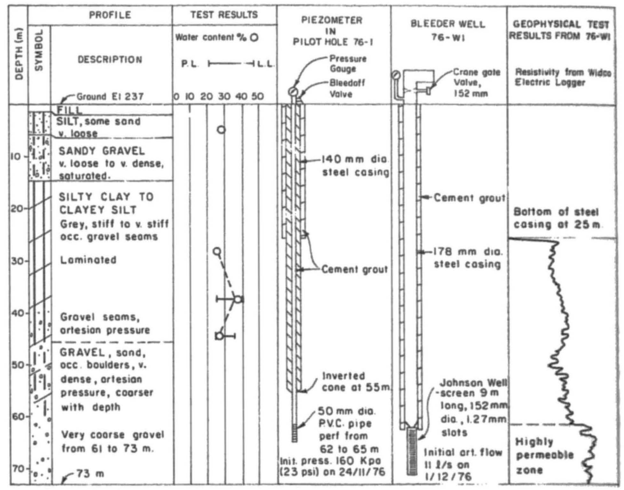

Fig. 11. Typical Drillhole Log

INSTALLATION OF BLEEDER WELLS IN 1976

In 1976 pilot holes 76-1, 76-2 and 76-3 were drilled in an area where pervious sand and gravel had been identified by drill hole sampling. Soil samples were recovere from the pilot holes and a Widco Electric Logger was used to determine the depth of the most continuous permeable zone suitable for installation of a bleeder well (see Fig. 11). A piezometer was installed in each of the pilot holes to provide additional monitoring of the artesian levels.

Three bleeder wells were installed approximately six metres from the pilot hole piezometers. Bleeder wells 76-W1, 76-W2 and 76-W3 were installed to depths of 72.5 m, 92.5 m and 87 m respectively. The lower 9 m of each well consists of six 1.5 m lengths of stainless steel Johnson well screen. The well screens, 152 mm diameter with a 1.27 mm slot size, were swedged tight with a lea packer to the bottom of the 203 mm O.D. steel casing. Typical bleeder well and piezometer installations are shown on Fig. 11.

Each well was developed continuously for 2 days after installation by jetting and pulsing alternately with high pressure air and water followed by periods of natural artesian flushing, see Fig. 12.

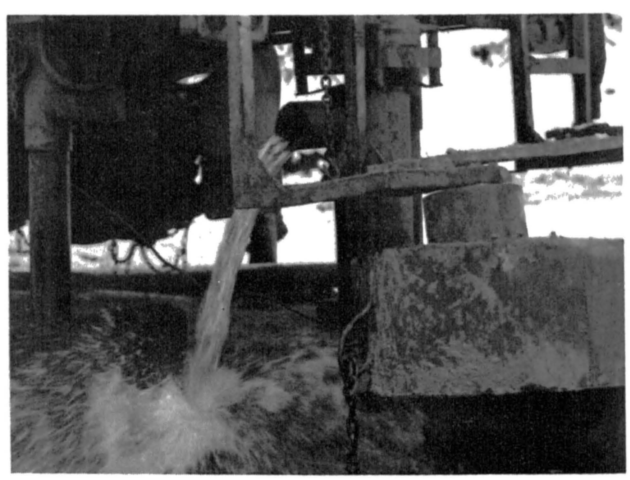

Fig. 12. Clear water from Bleeder Well 76-W1, immediately after development, January 1977

This method of development subjected the aquifer near the well screen to higher pressures than would occur under artesian flow conditions. This removed fine silt and sand from around the well screen producing a well-graded natural granular filter. After development, all wells yielded perfectly clear, silt-free water and have been clear every since. After completion of each bleeder well they were boxed in and are used as piezometers except during bleeder well operation, see Fig. 13 for a typical completed installation.

Fig. 13. Bleeder Well 76-W1, typical Housing in background, January 1977

Every year in January each bleeder well is tested on different days, by completely opening the valve and allowing the artesian water to flow unrestricted for 30 minutes. The free flow of artesian water from each bleeder well has to date always been clear and averages about 23 l/sec.

The 1977 and 1978 bleeder well test results were analyzed and described in a paper by Wade & Taylor (1978). Tests performed immediately after the bleeder wells were installed indicated that the drawdown effect from any one of the three wells produced a significant reduction in artesian pressure over a considerable distance from the bleeder well.

From January 14 to 24, 1977, Bleeder Well 76-W3 was opened and readings were taken of the piezometric levels in the piezometers around the Powerhouse No. 1. The results, shown on Fig. 14, are plotted as a cone of depression from Bleeder Well 76-W3. With a 15 m reduction in pressure head at the bleeder well, a drawdown of about 5 m was observed at Powerhouse No. 1, approximately 425 m from the bleeder well.

Further tests carried out in April 1978 confirmed that a single bleeder well alone would be capable of halting rapidly rising artesian pressures at Powerhouse No. 1. The criteria for operating the bleeder wells was prepared for the Operating Staff to follow in their long term protection of the powerhouse.

The aquifer characteristics determined from the April 1978 tests indicated a storage coefficient ranging from 1.5×10^{-5} to 5.0×10^{-4} (dimension less) and a transmissibility coefficient ranging from 0.75×10^5 to 1.5×10^5 litres/day/metre. As the test progressed the drawdown rate increased due to the boundary effects of deep bedrock limiting recharge to the aquifer. Given the complex boundary conditions, and the difficulty of establishing the rate of aquifer recharge it was considered impractical to analytically predict future artesian pressures.

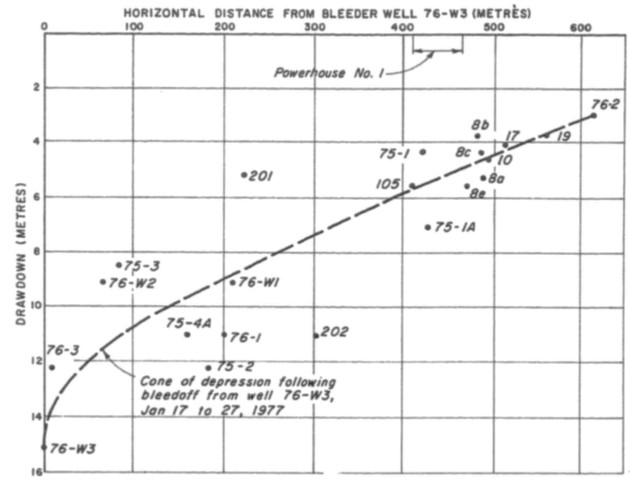

Fig. 14. Artesian Pressure Drawdown due to Opening Bleeder Well, January 1977

BLEEDER WELL TESTS, 1983

Between January 1978 and January 1983 it had been expected that it would be necessary to operate the bleeder well system, however, the mean peak artesian pressure in these years remained below El. 253 and therefore operation of the system was not required. It was decided that a full scale test should be simulated to evaluate the effectiveness of bleeder well operation procedures. Specifically it was required to determine whether the average artesian pressure could be truncated for an extended period of time at a pre-selected pressure.

This was successfully accomplished, as indicated by the results on Fig. 15, and the average artesian pressure was held at El. 249.6, with only minor variation, for a period of 6 weeks. Bleeder well 76-W1 was closed when the natural decline in artesian pressure went below El. 249.6.

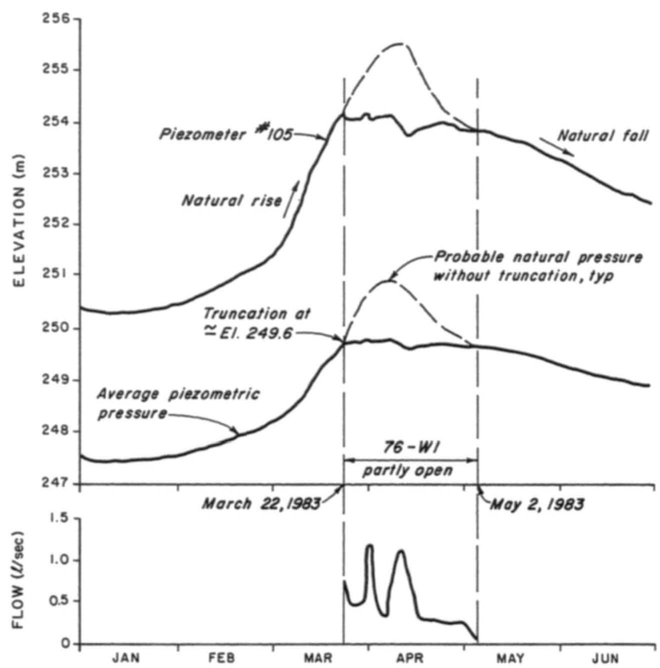

Fig. 15. Bleeder Well Test Results, 1983

DISCUSSION OF GROUND CRACKING AND THE EFFECTIVENESS OF THE OFFSHORE FILL AND BLEEDER WELLS

In the early 1950's Dr. Terzaghi assessed the geological conditions at the site and determined that artesian pressures created uplift beneath the clayey silt stratum causing cracking, and recommended placement of an offshore fill, following an unsuccessful attempt to install a satisfactory bleeder well system. He indicated that the offshore fill would increase the factor of safety against rotational movement due to high uplift pressures. Recent calculations indicate that the offshore fill increased the factor of safety by about 30 to 45 percent depending on whether the artesian pressures were low or high respectively.

In early 1974, uplift pressure under the offshore fill is assumed to have caused further cracking. For some time there was no evidence of differential settlement on one side of the crack with respect to the other side. However slumping on the lake side of the offshore fill was observed a week or two after the initial cracks appeared.

In late 1974 Dr. Hardy recommended installation of bleeder wells and limiting the artesian head beneath Powerhouse No. 1. In 1977, after installation of the bleeder wells, it was recommended that the artesian pressure be truncated if it rises above El. 253 m. Analysis of uplift beneath the offshore fill indicates that truncating the artesian pressure at El. 253 m. provides a factor of safety of about 1.2 compared with the condition of the artesian pressure causing uplift in 1974.

It is considered that both the 1950 and 1974 cracking events were initiated by uplift possibly followed by rotational movement. Whether the toe of a rotational movement had surfaced or whether a ridge due to artesian uplift was formed offshore on the lake bed surface could not be determined without extensive investigation including drilling and testing around the powerhouse and in the lake.

The approach adopted, after the 1974 cracking was to concentrate on controlling the artesian pressures by installing bleeder wells and assessing their merits rather than conducting an exhaustive study of potential failure mechanisms. Consequently the effectiveness of the offshore fill and bleeder well system will provide long term security to Bridge River Powerhouse No. 1.

CONCLUSIONS

High artesian pressures below the dense till foundation of Powerhouse No. 1 caused ground cracking in 1950 that resulted in movement of the powerhouse.

On the advice of Dr. Terzaghi sensitive instruments were installed to measure powerhouse tilt and penstock elongation. Also on the advice of Dr. Terzaghi a counterbalancing offshore fill was placed in front of the powerhouse.

Except for cyclical movement of the powerhouse no adverse ground movement occurred between 1951 and 1974. In 1974 further ground cracking occurred near the powerhouse due to exceptionally high artesian pressure.

With further exploration and testing a bleeder well system was successfully established that can be used, when required, to truncate the peak artesian pressure under the powerhouse.

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